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Development of Connection Technology between Multi-Point Press and Flexible Mold for Manufacturing Free-Form Concrete Panel

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Abstract: Many studies have been conducted for the accuracy of free-form concrete panel fabrication, but there still are errors in the process of fabrication. This study developed a connection technology of detachable shape part that can be applied to the existing multi-point Computer Numerical Control (CNC) to enhance the accuracy of fabrication. The detachable type can place a silicone plate on top of the rod without additional fixtures. The accuracy of the technology was verified by curvature test and free-form concrete panel fabrication test. Three curves were created to compare the discrepancies between the designed shapes and the fabricated shapes through quality test. As a result, the detachable type decreased the error by up to 2 mm. In addition, a panel was fabricated to analyze the error to verify the rigidity of the developed molds. The error caused by concrete deflection under load or the error caused by repeated fabrication was about 0.5 mm. The shape error was within 3.5 mm. This small error proved greater accuracy compared to the existing technology.

Keywords: free-form building; free-form mold; flexible mold; multi-point computer numerical control; free-form concrete panel

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1. Introduction

Free-form buildings refer to the structures that are not rectangular but tilted, narrowed, deformed, or have free curves as a whole or partially [1]. Nowadays, the technology to build free-form buildings is constantly evolving [2]. It is possible to see the development of technology by comparing the latest free-form buildings to the past buildings [3]. With the development of computer technology, it is becoming easier to engineer free-form buildings with geometric shapes. Engineers can use Building Information Modeling (BIM), such as Rhino, CATIA, and Revit, to easily express and modify curves, distortions, and free forms [4,5]. However, it is still very difficult to build an exterior with complicated designs [6,7].

Free-form buildings, in contrast with formal architecture, cannot be built out of a single massive mold as the exterior consists of curves [8]. Therefore, the free-form exterior is divided into panels that can be fabricated and constructed separately [6]. For example, the Sydney Opera House consumed around 10,000 sheets of free-form concrete panels to complete the shell-shaped roof, and Louis Vuitton Maison Seoul was completed in 2019 using about 19,000 sheets of free-form concrete panels [9]. In addition, the Dongdaemun Design Plaza (DDP) used about 40,000 pieces of free-form metal panels. About 76,000 free-form concrete panels was used to fabricate the 316 roof disks of the National Museum of Qatar [10]. About 20 different panels were fabricated to complete a single disk and about 150 disks with different curvature were fabricated to cover the entire museum [11]. In order to build the roofing on top of the museum, about 3000 molds were fabricated to complete the panels that were unique in shape [12].

Each free-form panel has a unique curvature, shape, and size, and the molds cannot be reused. With a greater number of molds to fabricate, it consumes a considerable amount of time and labor. This leads to greater cost of materials and waste disposal to delay the construction period and increase overall cost. The total construction cost of the Sydney Opera House was about 120,000,000 USD, which was 15 times greater than the initial estimate, and the cost of constructing the Guggenheim Museum Bilbao increased to 127,000,000 USD by 14 times [13–15]. Many other free-form buildings, such as the MIT Stata Center and Walt Disney Concert Hall, consume more than they cost due to technical limitations [16].

In particular, free-form panels can hardly be accurate due to the manual processes. In the case of free-form concrete panel (FCP) fabrication, the thickness of materials can vary according to the skillfulness of workers in surface treatment, as concrete has a flexible characteristic. In addition, quality issues are likely to occur as even the same team of workers can deliver inconsistent accuracy each time [17,18]. When there are errors in the fabrication process, even a small error can cause gaps between the panels in the assembly stage, and the accumulation of errors leads to construction errors. Severe construction errors lead to re-fabrication of panels for re-construction. Some technologies have applied Computer Numerical Control (CNC) devices to fabricate highly accurate molds out of various materials, but all of them have still failed to resolve the problem of disposable molds. Many studies have applied CNC devices to develop mold fabricating equipment and resolve these issues. The CNC devices receive the engineered curves in numerical data and fabricate the molds through mechanical movements. This technology significantly reduces the time and cost required to build free-form buildings, but it has caused shape errors due to the variables in the mold fabrication process. Therefore, it is necessary to improve the accuracy of free-form concrete panel fabrication technology for high-quality shapes. For that purpose, the current study aimed to improve the multi-point CNC technology for mold fabrication. The new method can modify the shape of molds as it moves countless rods to create the curves. However, the accuracy of curvature varies according to the materials of molds and the types of connections, resulting in errors. Therefore, the current study suggested the connection technology of shape part suitable for the multi-point CNC to enhance the accuracy of curvature fabrication and tested the accuracy of the technology. The study consisted of four sections:

1. Analysis of limitations of the existing multi-point CNC technology.
2. Development of multi-point CNC's connection technology of shape part.
3. Testing the accuracy by testing the shapes of curves.
4. Testing the technology by fabricating free-form concrete panels.

2. Preceding Studies

2.1. Free-Form Trim Molds

Computer Numerical Control (CNC) has constantly improved the free-form panel fabrication technology. However, most projects experience decreased productivity and significant costs as free-form molds are impossible to reuse [19]. Therefore, various technologies have been developed to successfully execute the free-form buildings projects. In case of free-form concrete production, free-form panels were produced using CNC-processed wood [20,21], textile [22], Expandable Polystyrene (EPS) [13,17,23]. However, CNC processing technology consumes a lot of resources as the materials cannot be reused, although it can ensure the accuracy of concrete shapes. As a solution, Gramazio developed reusable molds using wax [24]. He suggested only the concept of the equipment and technology and failed to mention any problems and solutions related to the fabrication of molds, such as the curing time of wax, crystallization, strength, and cracks. In addition, Gramazio did not test the capacities to form wax molds and the errors and failed to suggest the specifications of equipment for fabricating free-form wax molds. Donghoon Lee used CNC machines to develop reusable Phase Change Materials (PCM) fabrication technology [17,19]. He used mixed PCM to fabricate free-form molds to prevent the crystallization that occurs due to the characteristics of PCM. However, this method consumes a considerable amount of time because the top and lower molds should be fabricated separately for a single free-form concrete panel and PCM should be liquefied and cured for reuse. In addition, wax molds should be processed redundantly in order to be reused and the molds cannot be modified without reprocessing.

2.2. Flexible Mold

2.2.1. Lower Mold

In order to produce free-form panels with unique shapes most economically, the molds should be reusable. One of the solutions would be flexible molds. Flexible molds were first mentioned by Renzo Piano in 1960 and the height of actuator was adjusted using computer processing technology to modify the molds [25]. This triggered active study of flexible molds using supportive structures and CNC. Huyghe and Schoofs fabricated molds that can be modified using plywood and wires [26]. Grooves were made on MDF plywood and thin wires were inserted for the rods to support. The plywood itself could not be the molds because of the grooves, so it was covered with a silicone board to fabricate the panel. However, the plywood did not bend according to the engineered shape, creating a gap between the rods and the silicone board. Janssen developed a flexible lower mold for single and double curves to fabricate panels [27]. For single curves, concrete was poured over flat molds and transferred to height-adjustable wooden panels after a certain period of time to create the curves. For double curves, wooden strips were used to fabricate the shape panels that were supported by a pin bed to prevent gaps between the rods and the plywood. Since concrete is first poured to create the curves, it is important to determine the right time to deform the mold. Eigenraam used plastic strips to create the curves and engraved notches on the strips to reduce errors [28]. The curves created by the molds showed less than 4 mm errors, but the rigidity of molds could not be verified as the concrete panels were not fabricated. Adapa used the CNC technology to develop flexible mold equipment [29]. He designed rod systems and silicone protection to generate interaction between the two elements according to the type of molds. The protection with a smooth surface was placed according to the position of rod systems.

2.2.2. Double-Sided and Side Molds

The lower mold equipment using the CNC technology cannot create double-sided curves at once when fabricating panels and the accuracy of shapes may be sacrificed due to the manual work of top part. As a solution, Jeong used the CNC technology to suggest the concept of double-sided multi-point press equipment that can fabricate the top and bottom curves of free-form concrete panels and Yun developed a double-sided multi-point press using the concept [30,31]. He also suggested the conceptual drawing and configuration of equipment and used the curve creating method applied to the equipment to test the accuracy of curves. However, the actual equipment could not be used to fabricate the curvature and panels to test the performance and applicability of equipment. In addition, Yun developed side-mold control equipment to fabricate various free-form concrete panels [32]. The rods were placed in a circle and the number and moving value of rods were entered for various shapes according to the engineered shape. The panels were fabricated using the developed equipment to test the accuracy of fabrication. Raun suggested the concept of edge control that can precisely control the side angle to guarantee that the angle of the edge can be vertical according to the curvature of panels [33]. The angle-adjustable handle was installed on the edge of the mold and the edge and slope of lower mold was made similar to make the side mold vertical. Raun simply suggested the concept, but did not fabricate any panel to test the rigidity of side molds.

2.2.3. Free-Form Concrete Panel Auto-Fabrication Equipment

Kyeong Tae Jeong and Yun developed a compressive auto-fabrication equipment that combines double-sided and side molds to fabricate free-form concrete panel with less labor [32,34]. The free-form concrete panel fabrication equipment consisted of a double-sided multi-point press that forms double-sided curves based on CNC, side form control equipment for controlling the shape of panel and side angle, and flexible molds that were deformed according to the curvature and shape of panels. The fabrication process of free-form concrete panels was divided into four steps: connection, pouring, compression and curing, and removal. First, concrete is injected after connecting the top, bottom, and side molds according to the shape of panel. The injected concrete was compressed and cured in all directions using the mold equipment. Once the concrete was cured, the mold was removed and the fabrication was completed. The conceptual drawing of equipment explains the configuration, operating principles, and fabrication process of each equipment, but the performance verification of the equipment through panel manufacturing was not performed.

2.3. Free-Form Shape Analysis Technology

Creating free-form concrete panels requires highly advanced skills and the quality varies according to the technologies of workers and the accuracy of machines. A considerable amount of cost and time is consumed in case errors are occurred in the process of fabrication and construction due to the difficulties in making the geometric shapes. Due to these problems, many studies have used the following shape analysis technology to test the accuracy of panel fabrication. Min Shik Kim tested quality analysis to measure the degree of natural deflection of materials according to the concrete mixture [35]. For quality analysis, a free-form concrete panel that was 600 mm in width and length and 50 mm in thickness was fabricated and 36 nodes were bored at 100 mm interval to measure the variation in thickness. This method can directly check the variation in thickness of panels to check the rate of errors, but the shape can collapse due to the boring. In addition, the thickness should be measured by hand and it takes much time when analyzing the errors. Lim executed ANOVA and analysis of hypotheses based on the average of shape errors to test the quality of free-form concrete panels fabricated using the CNC machine [9]. The shape errors were measured 427 times to compare them with the coordinates of engineered panels. In addition, two hypotheses were tested: first, more errors were caused farther from the CNC machine and the errors caused by the machine are smaller than the allowable errors. Eigenraam used the 3D scanner to analyze the shape errors to check the accuracy of free-form curves [28]. Four curves were created to check the disposition of certain positions and the overall accuracy. As a result of error analysis, a maximum 4–5 mm error occurred at the edge of the molds and maximum error at the center was between 3 and 4 mm. Yun fabricated the free-form concrete panels and analyzed shape errors to check the accuracy [32]. As it is impossible to visually judge the errors, the 3D scanner and a quality test program were used to scan the fabricated panels and compare the errors to the scanned data. The minimum error was -2.471 mm and maximum error was 1.472 mm within $\pm$ 3 mm. The 3D scanner can identify the shape error fast and accurately, but the mechanical errors of the 3D scanner itself shall also be considered.

3. Development of Connection Technology of Shape Part of Multi-Point CNC

3.1. Analysis of Limitations of Existing Method

The current study was conducted to analyze the limitations of fixed-type multi-point CNC suggested by Jeong (2020) and improve it. The existing method connects the supporting rods to the silicone plate and creates the free-form curve by variating the height of rods. However, the bolt connection of rods and silicone plate causes limitations in regards to the curves. The two elements were connected perpendicularly, so the silicone plate was distorted when the rods rise. This did not lead to natural curves. In order to create accurate curves, Jeong (2020) developed multi-point CNC by applying joints to the rods so they can revolve according to the curvature. According to Figure 1, ball bearing is attached to the rods so the rods can revolve in every direction. As the rods revolve according to the curvature, they can prevent the distortion of silicone plate.3.

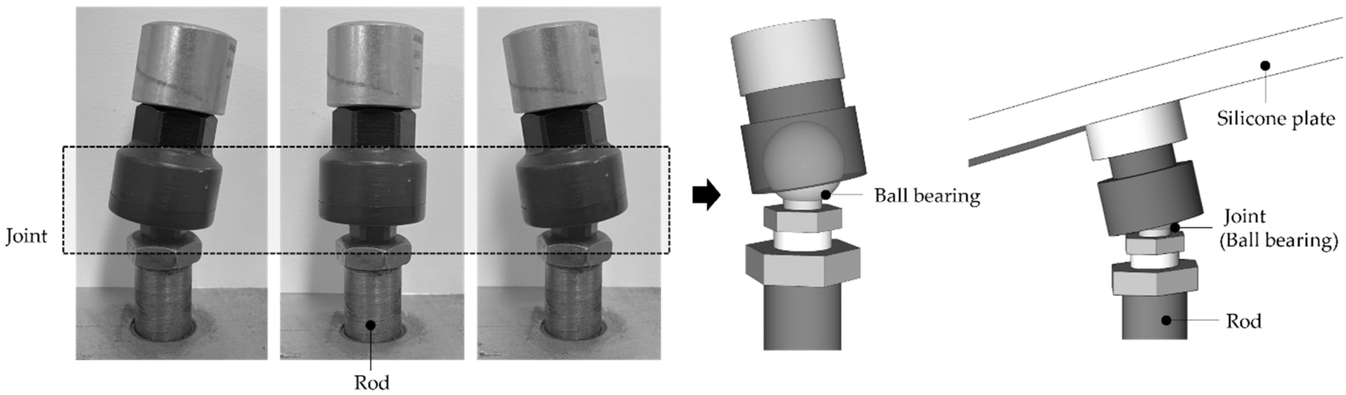


Figure 1. Fixed type.

However, the fixed type sacrifices the accuracy of shape forming due to the following reasons. First, the rods cannot revolve completely due to elasticity of silicone. When the fixed type was used to create a curve as shown in Figure 2, the silicone plate among the rods generated elasticity. The elasticity prevented the silicone plate from being straight and from revolving as much as the angle of joint in certain curves. Despite the bottom of silicone plate was lifted, the final shape did not match the engineered shape, resulting in error. In addition, the error may increase due to strong elasticity as the curvature of free-form curve increases. Therefore, there should be a connection type that eliminates the elasticity when connecting the rods to the silicone plate.

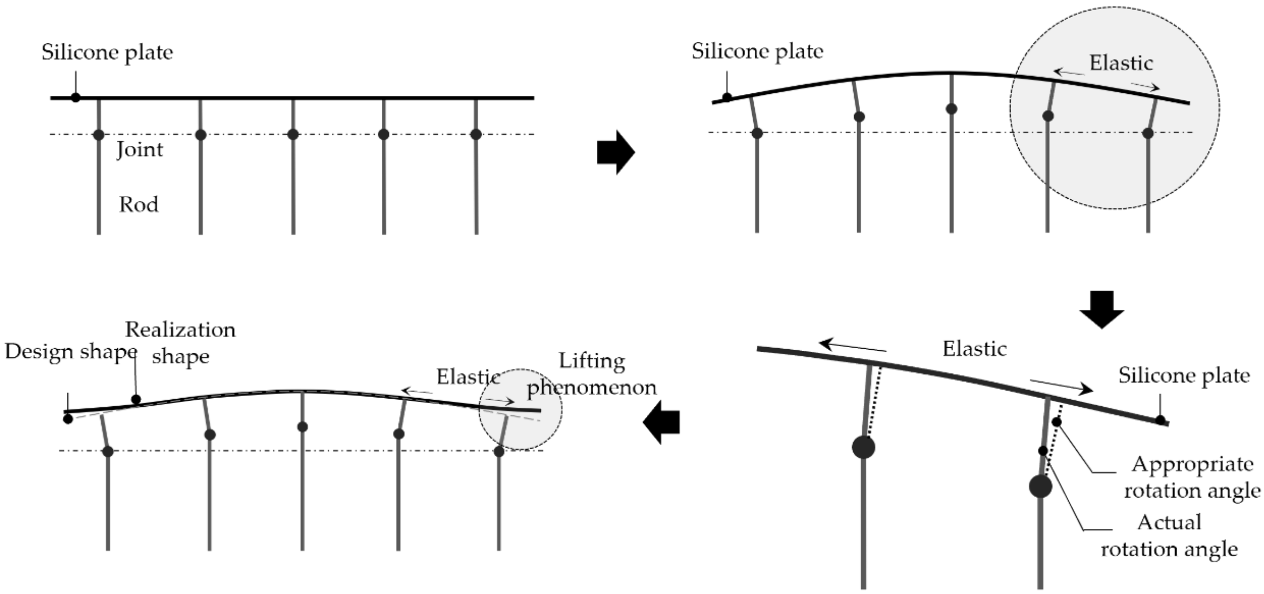


Figure 2. Limitation of revolving rods.

Second, the fixed-type molds aggravated the quality of surface of panels. Since the silicone plate was the surface on which concrete was poured, it needed to be smooth. However, the rods were bolted to the silicone plate as in Figure 3 to expose the bolts over the plate. When a panel was exposed, the surface became uneven, resulting in a lower quality product that required more processing. Additional materials can be used to cover the panel, but this can also create unevenness on the surface of panels. Therefore, a new method of connection was needed to keep the surface of silicone plate smooth.

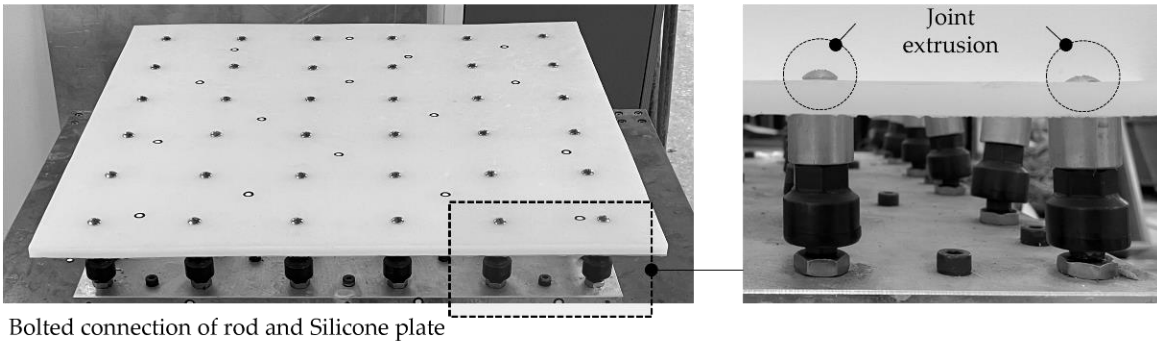


Figure 3. Surface of fixed-type molds.

Third, shape error occurred due to the deflection of concrete by load. The fixed type fabricates free-form curves by variating the height of rods, but it has limitations in bearing the load of concrete when fabricating the panels. As the rods were arranged at regular interval as in Figure 4, only the bolted part can support the load of concrete. When the curve was formed and the concrete was poured in this state, the concrete deflected where it was not supported. Due to these limitations, the fixed-type mold lost accuracy of curves. The panels cannot be accurate because of these limitations.

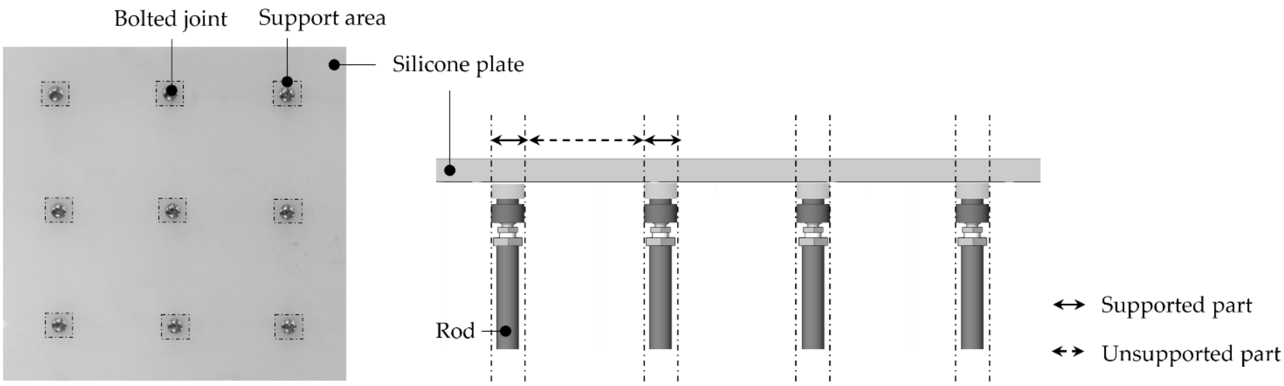


Figure 4. Limitations of bearing the load of concrete.

3.2. Development of Detachable-Type Connection Technology of Shape Part

Due to the aforementioned limitations, the current study developed the detachable-type technology to connect the rods to the silicone plate. The detachable type has the same bearing structure and shape part as the fixed type, but the silicone plate was placed on the rods without fixing. Therefore, additional connection parts were needed so the rods could support the silicone plate. For that purpose, the study developed a silicone cap as shown in Figure 5. The silicone cap consisted of rod fixing part, buffer part, and shape bearing and it was placed on top of the joints of rods. It was easily detached and can easily be fixed without additional connection as it caused friction because it was the same material as the silicone plate. The detachable type attached the silicone cap to the rods and raised the rods according to the engineered shape. When the silicone plate was placed on top of the rods, the joints revolved freely to create curves. This method separated the two elements, so the connection did not generate any elasticity and unevenness to create a smooth surface and curve.

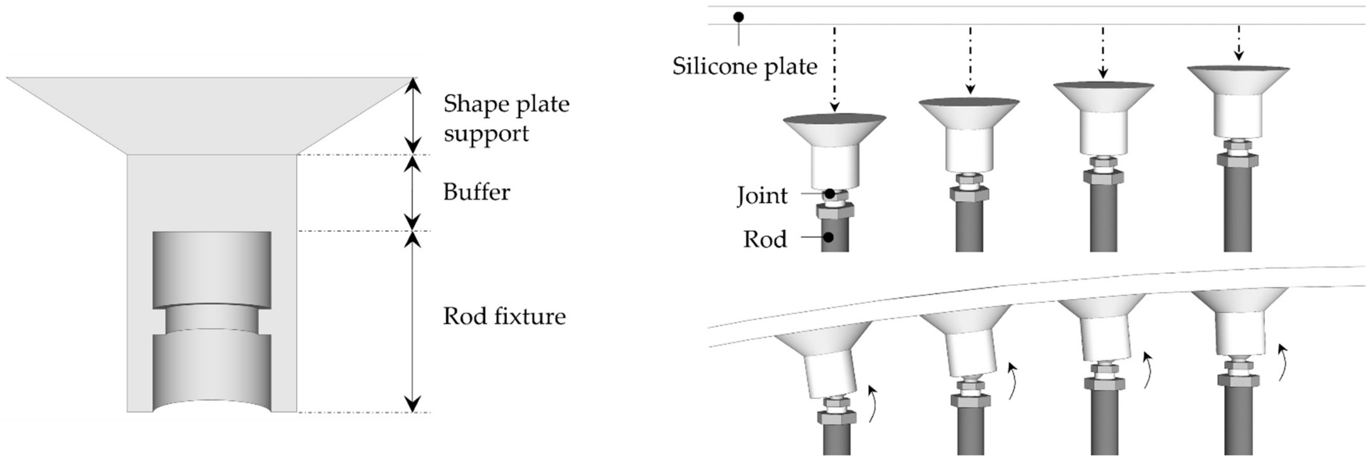


Figure 5. Detachable-type silicone cap.

In addition, the detachable type with silicone cap bears the silicone plate over a large area as in Figure 6. The supported part was much wider than the unsupported part, so it can prevent any deflection caused by the load of concrete. When viewed from the top as in (A), the top part of silicone cap bearing part is elevated when concrete gains load because silicone is elastic. Therefore, it can bear most of the surface of the shape part.

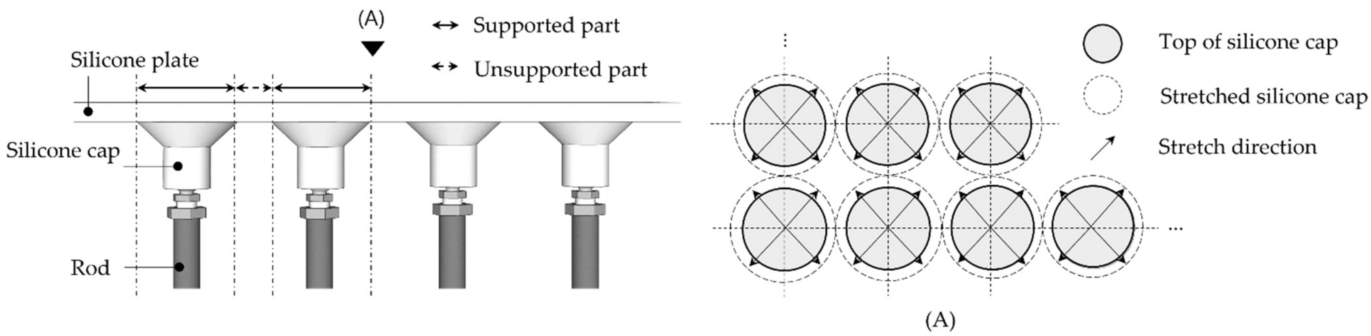


Figure 6. Concrete load bearing in silicone cap.

In order to confirm that the connection technology suggested in the current study can fabricate accurate shapes, a test was conducted to create the curves. The existing fixed type and detachable type were applied to a manual multi-point press to create the curves and check the shape errors. The curves are tested as follows: first, a curve is engineered and the rods' moving value was calculated. When the rods were elevated to create a curve, the engineered shape was compared to the curve to analyze the errors. At that time, the errors of machines used to analyze the errors were not considered.

As shown in Figure 7, three 600 mm $\times$ 600 mm single curves were engineered to match the size of silicone plate. Curve 1 has no point of inflection and the perpendicular variance of curve at 300 mm was 30 mm. Curve 2 has no point of inflection and the perpendicular variance of curve at 150 mm was 20 mm. Finally, Curve 3 has the point of inflection at the center of silicone plate and the perpendicular variance of curve at 150 mm and 450 mm was 10 mm.

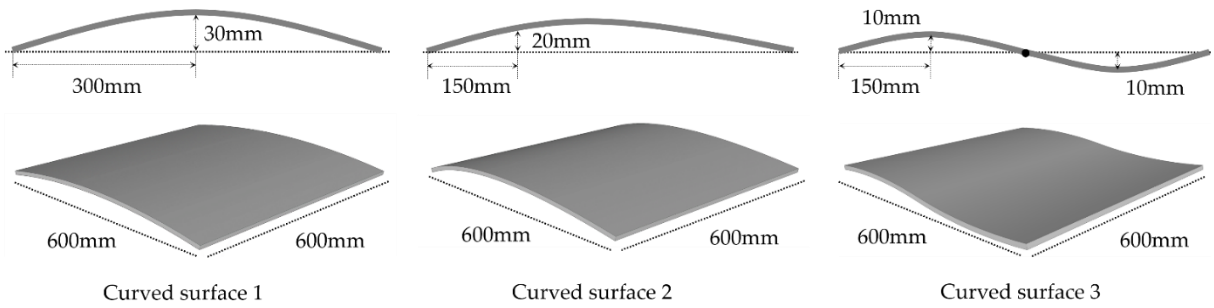


Figure 7. Engineering free-form curves.

As a result of calculating the rods' moving values according to the engineered shape, the moving values of Rods Y1 through Y6 were equal as described in Table 1 and the values for X1 through X6 were all different. The X value of Curve 1 was 19.2–39.2 mm and the X value of Curve 2 was 17.7–34.7 mm. The X value of Curve 3 was 10.0–30.0 mm.

Table 1. Moving values of rods by curve.

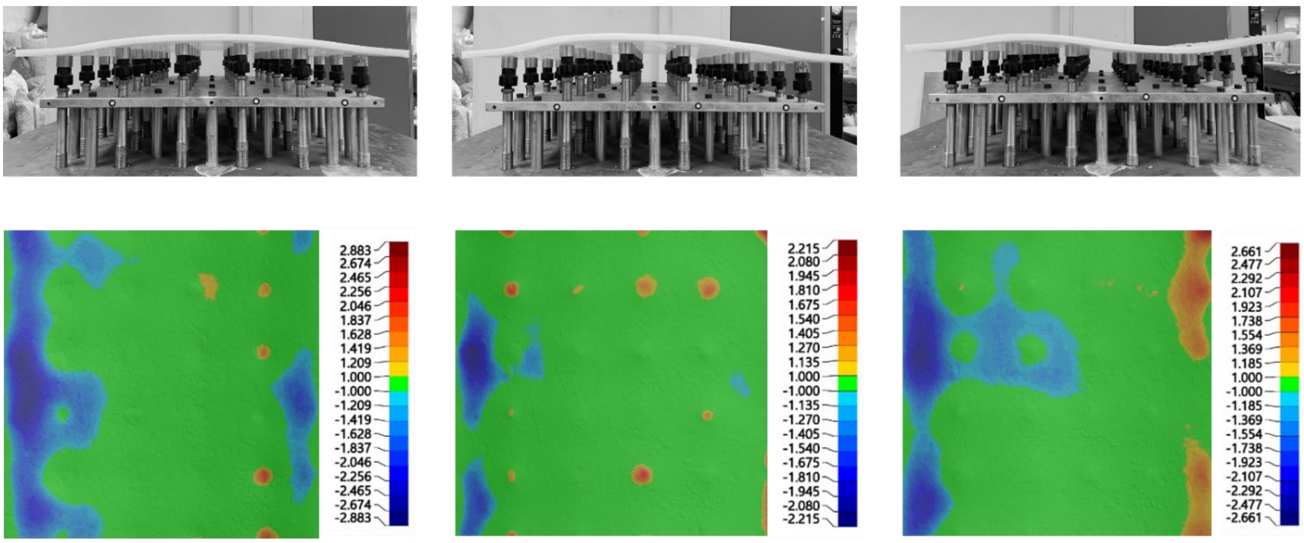
		X_1	X_2	X_3	X_4	X_5	X_6
Y	Curved surface 1	19.2	32.6	39.2	39.2	32.6	19.2
	Curved surface 2	17.7	30.0	34.7	32.5	25.5	15.5
	Curved surface 3	25.6	30.0	25.6	14.4	10.0	14.4

The rods were lifted according to the moving values to create a curve on the silicone plate. It was impossible to visually see the error of the curve, so a 3D scanner (GoCanSpark) and quality test program (VXInspect) were used. The 3D scanner was used to scan the shape and the quality test program was used to compare the scanned data to the engineered shape to analyze the errors between the two shapes. The range of analysis of errors was limited to the part supported by the outermost rods to collect data. The–value of data indicated that the rods were lower than the standard shape, while the + value indicated that they were higher. As in Table 2, the fixed type of Curve 1 showed errors between −2.883 mm and 2.008 mm and the range of error was 4.891 mm. The detachable type showed errors between −1.376 mm and 1.688 mm and the range of error was 3.064 mm. The detachable type's shape error decreased by 1.827 mm compared to the fixed type. In case of Curve 2, the fixed type showed errors between −2.215 mm and 2.204 mm and the range of error was 4.418 mm. The detachable type showed errors between −1.671 mm and 1.218 mm and the range of error was 2.889 mm. The shape error of detachable type decreased by 1.529 mm compared to the fixed type. In case of Curve 3, the fixed type showed errors between −2.550 mm and 2.661 mm and the range of error was 5.211 mm. The detachable type showed errors between −1.578 mm and 1.565 mm and the range of error was 3.143 mm. The shape error of detachable type decreased by 2.068 mm compared to the fixed type.

Table 2. Shape error by connection technology according to the shape of curve.

	X_2	Min	Max	Std.Deviation	Error Range
Curved surface 1	Fixed	−2.883	2.008	0.760	4.891
	detachable	−1.376	1.688	0.469	3.064
Curved surface 2	Fixed	−2.215	2.204	0.604	4.418
	detachable	−1.671	1.218	0.437	2.889
Curved surface 3	Fixed	−2.550	2.661	0.833	5.211
	detachable	−1.578	1.565	0.531	3.143

Considering the fixed-type curve as in Figure 8, Curved surface 1 showed the greatest error at the edge of shape. Due to the difference in the height of rods, the silicone's elasticity straightened the shape panel and lowered the rods of CNC. Curved surface 2 caused errors due to the strong elasticity around the edges and the greatest error was found at the left edge where the difference in the height of rods was greatest. In addition, the bolt connection exposed the bearing points to elevate the shape higher than the standard shape and caused errors. In case of curved surface 3, the convex part to the left of the deflection point caused errors lower than the engineered shape and the concave part to the right caused errors higher. With a greater difference in rod height, curved surfaces 1 and 2 revealed more errors. However, Rod 3 showed greater errors around the edges, and not at the center where there was the greatest difference in height. The shape of curve changed by the deflection point and the elasticity was offset to cause less error.



(a) Curved surface 1 (b) Curved surface 2 (c) Curved surface 3

Figure 8. Shape error of fixed type.

The detachable type showed errors less than ±1.000 mm in all three curves as in Figure 9. However, there were shape errors at certain parts, seemingly because the equipment was operated manually. As a result of creating the three curves and analyzing the errors, the error of detachable type was smaller than the error of fixed type. It was concluded that the connection technology of the detachable type suggested in the current study fabricated a shape more accurate than that of the existing technology. Therefore, the detachable-type connection method should be used when fabricating free-form concrete panels using multi-point CNC.

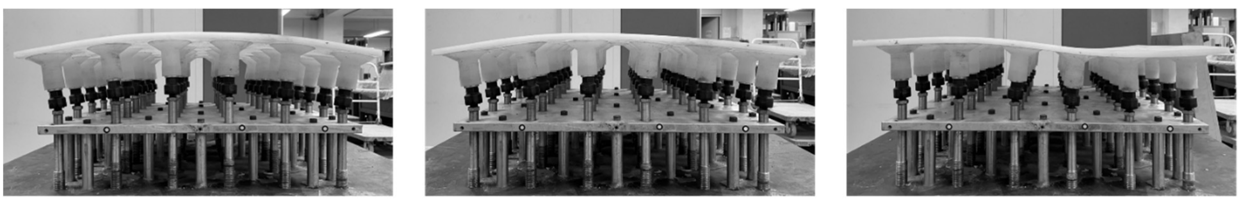
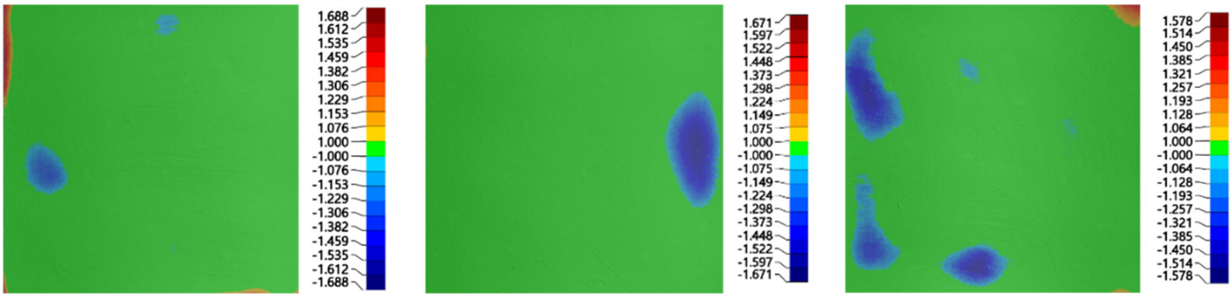


Figure 9. *Cont.*

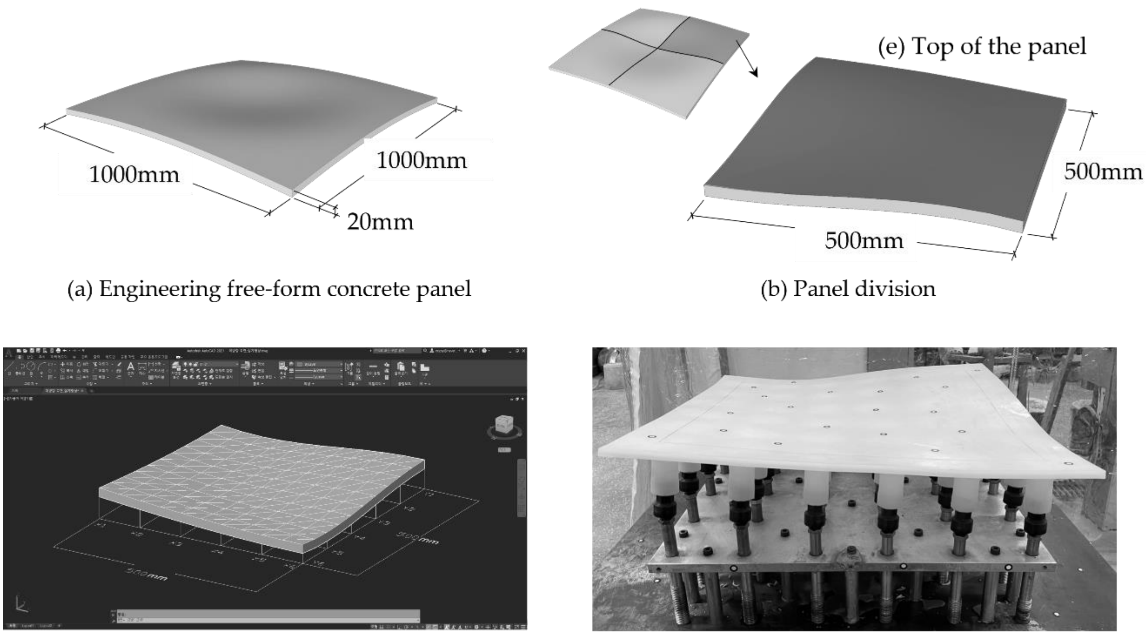


(a) Curved surface 1 (b) Curved surface 2 (c) Curved surface 3

Figure 9. Shape error of detachable type.

4. Free-Form Concrete Panel Fabrication Test

The aforementioned curve test confirmed that the technology suggested by the current study created a more accurate curved mold. However, errors may be caused by deformation of molds when it was actually used to fabricate the panels. Therefore, it was necessary to check the rigidity of molds to test the effect of technology. For that purpose, the current study used a manual multi-point press applying the detachable type to fabricate the free-form concrete panel according to the panel fabrication technology suggested by Yun (2021) [31]. First, a double-sided curve panel that was 1000 mm × 1000 mm with 20 mm thickness as in Figure 10a was engineered. Considering the maximum size of manual multi-point press, the panel was divided into four square panels that was 500 mm on one side as in Figure 10b. The top Figure 10e of the divided panel was a curve built with a mold, so the moving values of rods should be calculated based on the top part. Therefore, the panel was rotated by 180° and 3D CAD was used as in Figure 10c to calculate the moving values of rods. Once the moving values of rods were calculated, the rods were elevated according to them as in Figure 10d and a silicone plate was placed on top to create a curve.



(a) Engineering free-form concrete panel (b) Panel division

(c) Calculating moving values of rods (d) Forming mold curve

Figure 10. Shape engineering and curve forming.

The moving values of rods were calculated using the 3D CAD considering the joints and the moving values of rods of all four panels were equal as the divided panels were identical in shape as in Table 3.

Table 3. Moving values of rods of double-sided curve.

	X_1	X_2	X_3	X_4	X_5	X_6
Y_1	23.2	24.5	28.2	34.0	41.4	50.0
Y_2	16.9	17.0	18.3	23.2	31.7	41.4
Y_3	21.5	20.2	17.6	17.3	23.2	34.0
Y_4	32.1	29.4	23.1	17.6	18.3	28.2
Y_5	42.1	38.4	29.4	20.2	17.0	24.5
Y_6	46.1	42.1	32.1	21.5	16.9	23.2

The shape errors were measured to check the accuracy of mold curve. A 3D scanner was used to scan the curve and compare it to the engineered shape. As a result of error analysis, the errors ranged between −1.466 mm and 1.477 mm as shown in Table 4 and the range of error was 2.944 mm. As in Figure 11, most silicone plate showed ±1.000 mm errors. However, the error was about −1.500 mm in several tiny circles in the areas where the curvature changed radically as in (a). The silicone plate was pressed down by the force that bends inwards while forming the curve. As the silicone cap supported it, the center with greater bearing force showed smaller errors, but the edges with smaller bearing force showed greater errors. However, the measured errors were within 3.000 mm and the shape was not corrected because the errors did not exceed the allowable error of panel fabrication [9,17,18,31,32].

Table 4. Shape error of mold curve.

	Min	Max	Std.Deviation	Error Range
Shape error	−1.466	1.477	0.432	2.944

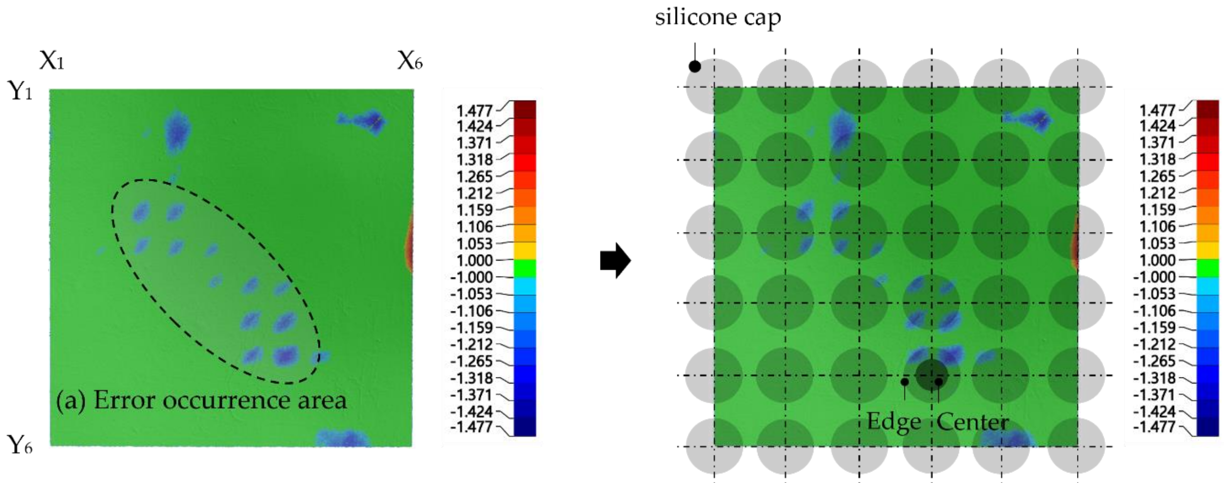
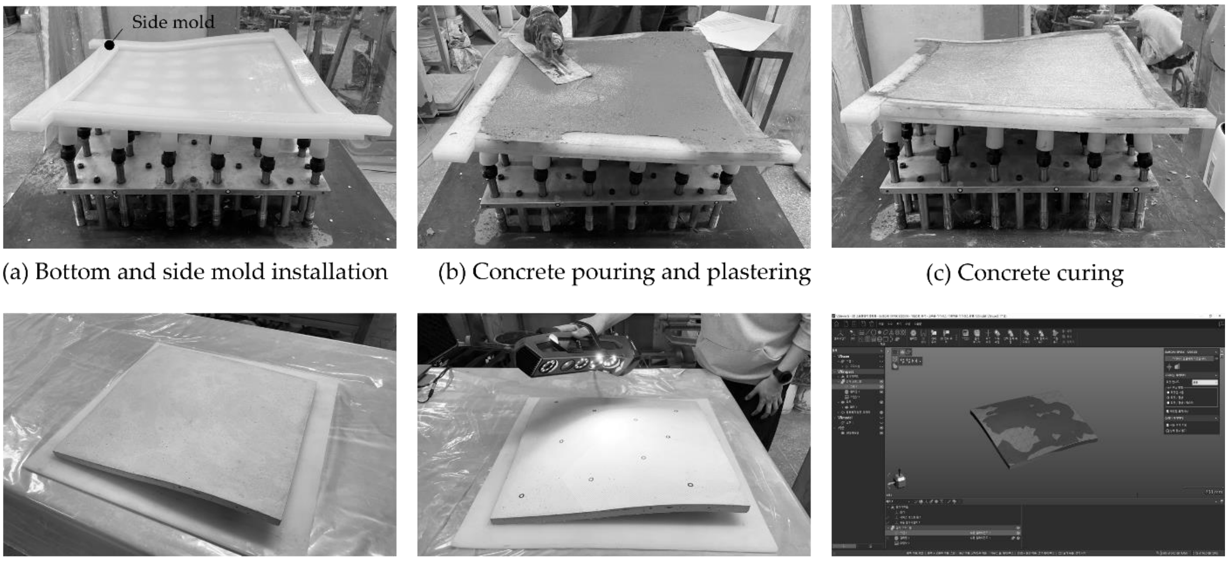


Figure 11. Shape error of mold curve according to the position of silicone cap.

As the mold curve's accuracy was proven by measuring the errors, the free-form concrete panel was fabricated as in Figure 12. The current study fabricated several panels that are 500 mm on one side using the same mold to fabricate a free-form concrete panel that is 1000 mm × 1000 mm. A side mold that was 20 mm in thickness was installed on the lower mold from the manual multi-point press as in Figure 12a, the right amount of concrete was poured to finish the top as in Figure 12b, and the concrete was cured as in Figure 12c. Then, the mold was removed to complete the fabrication as in Figure 12d. In order to analyze the shape error of fabricated panels, the panels were scanned as in Figure 12e and the quality of shape part was tested as in Figure 12f. Steps Figure 12a through Figure 12d were repeated to fabricate four free-form concrete panels and steps Figure 12e,f were repeated for the quality test.



(a) Bottom and side mold installation (b) Concrete pouring and plastering (c) Concrete curing

(d) Removing mold (e) 3D Scanning of panels (f) Shape quality test

Figure 12. Free-form concrete panel fabrication and quality test process.

The current study divided the panels to match the size of manual multi-point press, so shape error was analyzed for each panel. First, the shape error of Panel 1 and the curve error of mold were compared to see if there is any deflection caused by the load of concrete. This was the first panel where concrete was poured immediately after completing the mold and it is affected only by natural deflection as there is no error caused by the removal of mold and the disposition of shape panel. The deflection by concrete can be identified by comparing the errors between the curve of mold and the curve of the panel fabricated with the mold. As shown in Table 5, the curve error of the mold before pouring concrete was 2.944 mm and the curve error of the top of free-form concrete panel was 3.486 mm. The difference between the two curve errors was 0.542 mm. In other words, the deflection by the load of concrete was about 0.500 mm. As a result, there was an error smaller than 1.000 mm, manifesting that the silicone cap from the study has outstanding resistance against the load of concrete.

Table 5. Deflection error caused by the load of concrete.

	Min	Max	Std.Deviation	Error Range
Mold of the curved surface	−1.466	1.477	0.432	2.944
Free form concrete panel	−1.755	1.731	0.541	3.486
Deflection error				0.542

Next, the shape error of four panels was analyzed to check the error caused by repeated fabrication. As shown in Figure 13, the error was large in the center where the curvature changed sharply on Panel 2. However, the error at that part reduced as fabrication was repeated. This manifests that the deflection error was offset by the change in the revolving angle of rods and the bearing position of silicone cap with more fabrication. However, there were errors found on other parts and the overall error did not change.

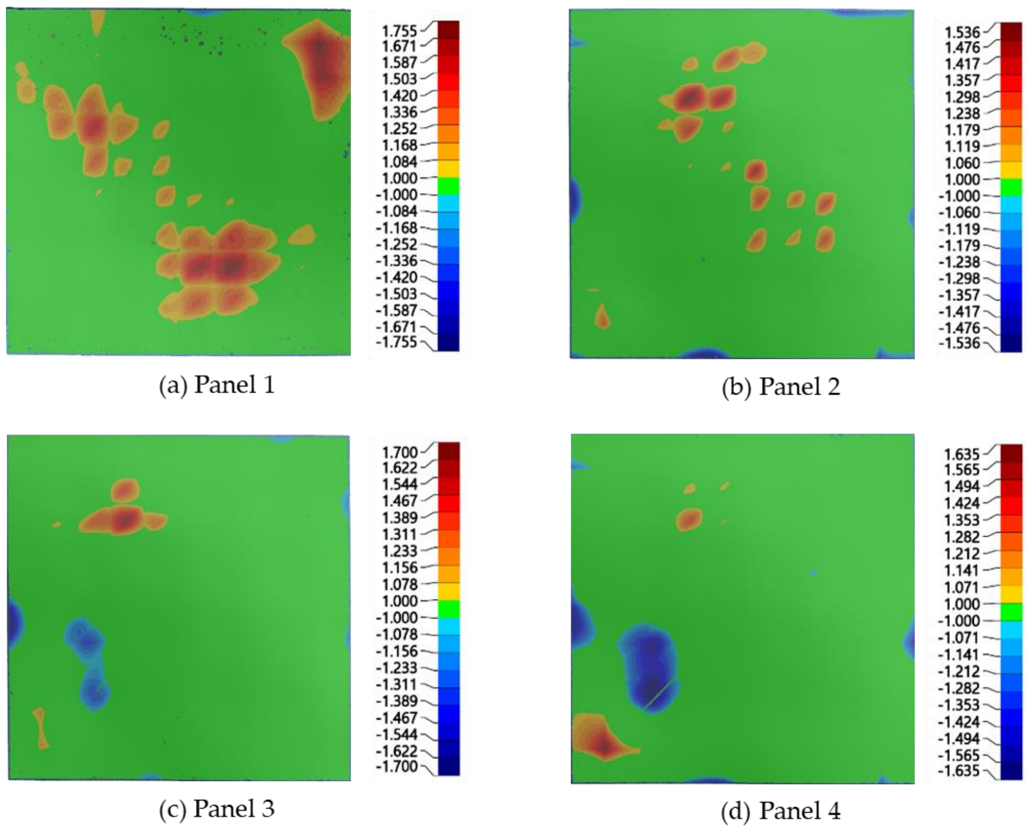


Figure 13. Shape error of free-form concrete panel in repeated fabrication.

The shape error of free-form concrete panel was 3.486 mm for Panel 1, 3.069 mm for Panel 2, 3.319 mm for Panel 3, and 3.270 mm for Panel 4 as in Table 6. The shape error did not show much change caused by repetition, but the shape error was measured to be within 3.000–3.500 mm.

Table 6. Shape error of free-form concrete panel.

Title 1	Min	Max	Std.Deviation	Error Range
Panel 1	−1.755	1.731	0.541	3.486
Panel 2	−1.536	1.534	0.550	3.069
Panel 3	−1.700	1.619	0.520	3.319
Panel 4	−1.635	1.635	0.544	3.270

The deflection by the load of concrete was about 0.5 mm and the shape error of panel was no larger than 3.5 mm. This was a very small error and it can be judged that the rigidity of mold was great for panel fabrication. However, it exceeded the allowable error of 3.000 mm and additional improvement would be needed to reduce the error to allowable error. The error of fabrication was about 0.5 mm, so it was necessary to correct the mold through the aforementioned reverse engineering, so the maximum error did not exceed 2.500 mm.

The panel assembled after the quality test of each panel showed minor errors as in Figure 14. This was because there was no rear space frame fixing the panel in place and the panel was not accurately positioned. Therefore, the overall panel would be almost free of errors when a rear space frame was installed to support the panel at the right height and calibration was inserted at a regular interval.

Figure 14. Final free-form concrete panel.

5. Conclusions

The current study developed a connection technology of shape part suitable for multi-point CNC, and it analyzed the limitations of the existing fixed type and developed the detachable type connection technology for improvement. The detachable type places the silicone plate on the rods without any fixtures. A silicone cap was placed at the end of each rod and the rods were elevated as engineered to place the silicone plate on top. Then, the joints revolved freely to create the curve. This method was easily fixed without additional fixtures and did not cause elasticity due to connection. In addition, it can create a smooth curve with no unevenness and prevent any deflection by concrete. For verification, the existing fixed type and the new detachable type were applied to create curves and analyze the shape error. The detachable type's shape error was smaller than that of the existing fixed type and the error reduced by up to 2 mm. This indicated that the shape was more accurate than the existing method. Panel fabrication test was conducted to test the errors that occur when the new technology was applied to fabricate the panels and the rigidity of the mold equipment. The error of the mold curve was within 3 mm, which was the allowable error suggested by the current study. Next, as a result of shape analysis after panel fabrication, the deflection by the load of concrete was about 0.5 mm. This was a minor error, manifesting that the detachable type suggested in the current study has excellent resistance against the load of concrete. The range of shape error caused by repeated fabrication was within 3–3.5 mm. There was about 0.5 mm of error, but it was a minor error, meaning that the rigidity of mold was also suitable for panel fabrication. The current study suggested a new technology to overcome the limitations of the existing technology and fabricated the panels to prove outstanding accuracy. Therefore, the technology would be able to fabricate high-quality panels. However, the shape error of the fabricated panels exceeded the allowable error suggested by the current study although it was very small. Therefore, additional studies would be required for the shape error to satisfy the allowable error in panel fabrication. In addition, the current study can only fabricate panels of certain sizes and additional studies would be necessary to fabricate free-form concrete panels for actual structures and test the accuracy in order to apply the new technology to real life.

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